論文の内容の要旨

Grain boundary diffusion creep of olivine and its role in upper mantle rheology

（オリビンの粒界拡散クリープと上部マントルレオロジーにおける役割）

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Olivine is the most abundant mineral in the Earth's upper mantle and its deformation properties have been intensively studied to understand mantle rheology. Diffusion creep is considered to be one of the major deformation mechanisms. However, the creep properties are controversial. Differences of up to two orders of magnitude in viscosity at the same grain sizes and temperatures have been reported from experimental diffusion creep studies on olivine aggregates. Based on the knowledge of material science, the difference in strength is likely to be due to slight difference in the chemical composition. In this study, I firstly established constitutive equations for olivine diffusion creep which include the effect of the chemical composition, and then calculated the viscosity-depth profiles for the oceanic upper mantle based on the established flow law.

I conducted one-atmosphere uniaxial compression experiments on fine-grained (~1 μm) Fe-bearing olivine ($Mg_{1.8}Fe_{0.2}SiO_4$) aggregates that were variably doped with CaO ± Al_2O_3. I identified power-law interface-controlled creep at low stresses and grain-boundary diffusion creep at high stresses, which operate as mutually coupled, i.e., sequential processes. I established constitutive equations for interface-controlled creep and diffusion creep of undoped olivine:

$$\dot{\varepsilon}_{\mathrm{int}}^{\mathrm{ref}} = 2.12 \times 10^{12} \mathrm{\mu m/MPa^3/s} \cdot (\sigma^3/d) \cdot \exp\left(-\frac{610\ \mathrm{kJ/mol}}{\mathrm{R}T}\right)$$

and

$$\dot{\varepsilon}_{\text{diff}}^{\text{ref}} = 1.12 \times 10^{10}\ \mu\text{m}^3/\text{MPa/s} \cdot (\sigma/d^3) \cdot \exp\left(-\frac{470\ \text{kJ/mol}}{\text{R}T}\right),$$

where $\dot{\varepsilon}_{\text{int}}^{\text{ref}}$ and $\dot{\varepsilon}_{\text{diff}}^{\text{ref}}$ are strain rates of interface-controlled creep and grain-boundary diffusion creep, respectively, σ is stress, d is grain size, T is absolute temperature, and R is the gas constant. Then I used the combined rate equation (i.e., $\dot{\varepsilon} = \left({\dot{\varepsilon}_{\text{int}}^{\text{ref}}}^{-1} + {\dot{\varepsilon}_{\text{diff}}^{\text{ref}}}^{-1}\right)^{-1}$, where $\dot{\varepsilon}$ is the bulk strain rate) as a reference to examine the effect of doping on creep rates. Ca and Al were found to enhance rates of both interface-controlled creep and diffusion creep above certain temperatures, and this effect becomes significant with increasing temperature. I attribute the rate enhancements to grain-boundary disordering promoted by grain-boundary segregation of the dopants at near-solidus (bulk eutectic temperature) conditions. The enhancements are well described in relation to the sample solidus and an additional activation energy relative to that of the reference creep state:

$$\chi_{\text{int}} = 1 \qquad \text{at } T \leq 0.84 \cdot T_{\text{s}},$$
$$\chi_{\text{int}} = \exp\left[-\frac{\Delta Q}{\text{R}} \cdot \left(\frac{1}{T} - \frac{1}{0.84T_{\text{s}}}\right)\right] \qquad \text{at } T > 0.84 \cdot T_{\text{s}}$$

and

$$\chi_{\text{diff}} = 1 \qquad \text{at } T \leq 0.92 \cdot T_{\text{s}},$$
$$\chi_{\text{diff}} = \exp\left[-\frac{\Delta Q}{\text{R}} \cdot \left(\frac{1}{T} - \frac{1}{0.92T_{\text{s}}}\right)\right] \qquad \text{at } T > 0.92 \cdot T_{\text{s}},$$

where χ_{int} and χ_{diff} are the enhancements of interface-controlled creep and diffusion creep rate, respectively, ΔQ is an additional activation energy (= 230 kJ/mol), and T_{s} is bulk eutectic temperature in K. Overall, the creep of doped olivine is well described in terms of $\dot{\varepsilon}_{\text{int}}^{\text{ref}}$ and $\dot{\varepsilon}_{\text{diff}}^{\text{ref}}$ with χ_{int} and χ_{diff} by:

$$\dot{\varepsilon}_{\text{int}} = \chi_{\text{int}} \cdot \dot{\varepsilon}_{\text{int}}^{\text{ref}}$$

and

$$\dot{\varepsilon}_{\text{diff}} = \chi_{\text{diff}} \cdot \dot{\varepsilon}_{\text{diff}}^{\text{ref}},$$

where $\dot{\varepsilon}_{\mathrm{int}}$ and $\dot{\varepsilon}_{\mathrm{diff}}$ are strain rates of interface-controlled creep and grain-boundary diffusion creep, respectively.

I estimated solidus temperatures of the samples used in the previous diffusion creep experiments. These temperatures were used to compare previously reported diffusion creep rates for olivine with my established diffusion creep law. I found that the law explains a difference of up to two orders of magnitude in olivine creep rates at the same temperatures, stresses, grain sizes, and water contents in the previous studies.

The geotherm normalized by the mantle solidus was calculated for the upper mantle with water contents ranging from 0 to 300 μg/g, which predicts depths where grain-boundary diffusion creep is enhanced due to grain-boundary disordering. Constructed viscosity-depth profiles reveal a very thin mantle lithosphere beneath mid-ocean ridges, with development of the lithosphere away from the ridge, leaving a low-viscosity region below. Given a grain size of 1 mm and depending on the water content, a viscosity of $2–5\times10^{19}$ Pa·s is predicted for the low-viscosity mantle beneath 50-million-year-old seafloor.